Sensitivity analysis of the rare decay $B_s \to \mu^+\mu^-$ with the DØ detector

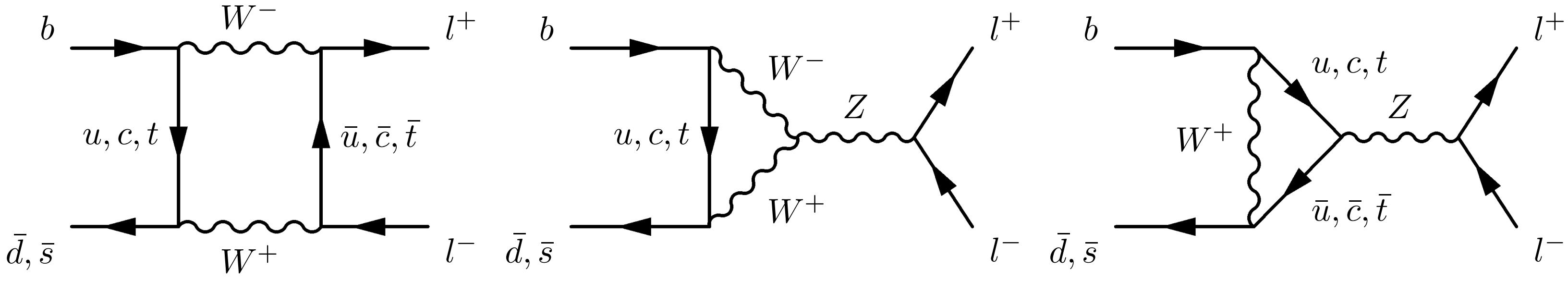
R. Bernhard
University of Zürich

PHENO 2004
27^{th} April, 2004

- Theoretical Background
- DØ Experiment at the Tevatron
- Analysis procedure
- Preliminary results
- Conclusions

Introduction to the $B_{d,s} \to l^+l^-$ decay I (SM)

Main contributing Standard Model diagrams



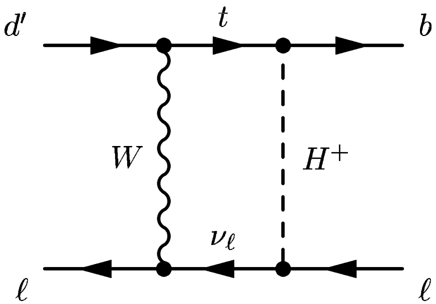
Theoretical predictions

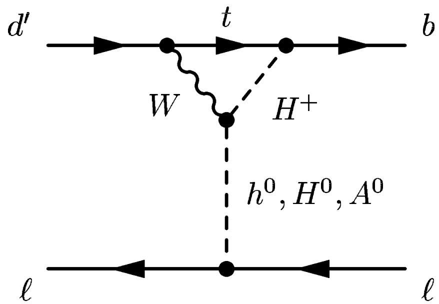
	$BR(B_d \to l^+l^-)$	$BR(B_s \to l^+l^-)$
l = e	$(3.4 \pm 2.3) \cdot 10^{-15}$	$(8.0 \pm 3.5) \cdot 10^{-14}$
l = μ	$(1.5 \pm 0.9) \cdot 10^{-10}$	$(3.4 \pm 0.5) \cdot 10^{-9}$
l = τ	$(3.1 \pm 1.9) \cdot 10^{-8}$	$(7.4 \pm 1.9) \cdot 10^{-7}$

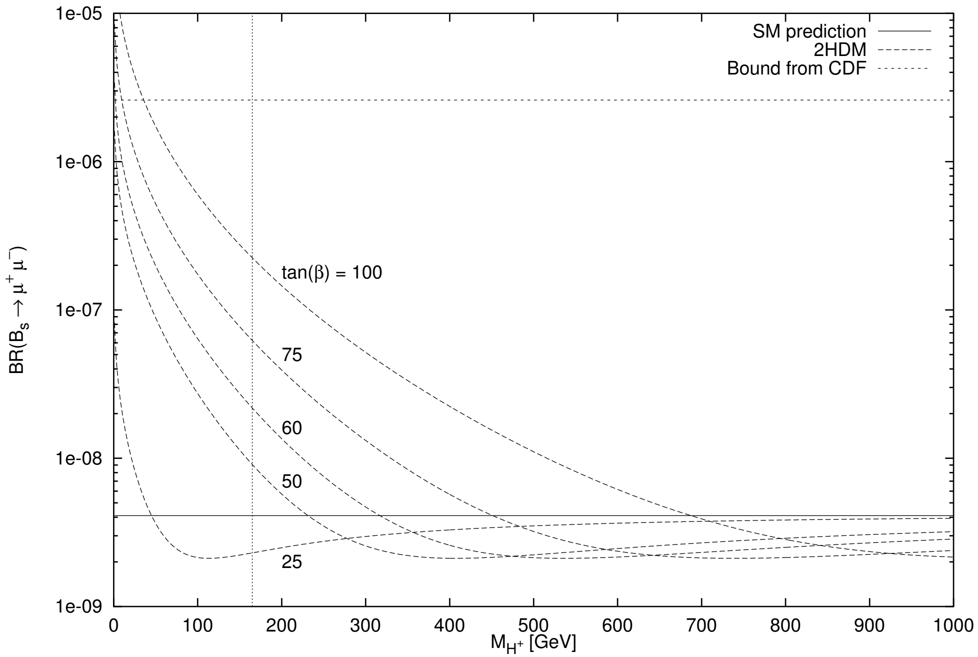
Experimental upper limits (at 90% (95%) confidence level)

	$BR(B_d \to l^+l^-)$	$BR(B_s \to l^+l^-)$
l = e	$< 5.9 \cdot 10^{-6}$	$< 5.4 \cdot 10^{-5}$
l = μ	$< 1.5(1.9) \cdot 10^{-7}$	$< 5.8(7.5) \cdot 10^{-7}$
l = τ	$< 2.5\%$	$< 5.0\%$

$B_s \to \mu^+\mu^-$ decay in SUSY (Two Higgs-Doublet Model)







- Parameters of the neutral Higgs sector cancel out
- Branching fraction depends only on charged Higgs mass and $\tan\beta$
- Branching fraction increases like $\tan^4\beta$ ($\tan^6\beta$) in 2HDM (MSSM).
- Mode is complementary to $b \to s\gamma$
- R parity violating models can give tree level contributions
- Mode is correlated to (g-2) in mSUGRA
- Also other models like e.g. $MSO_{10}SM$ predict large enhancement $\propto \tan^6\beta$

B physics at the Tevatron

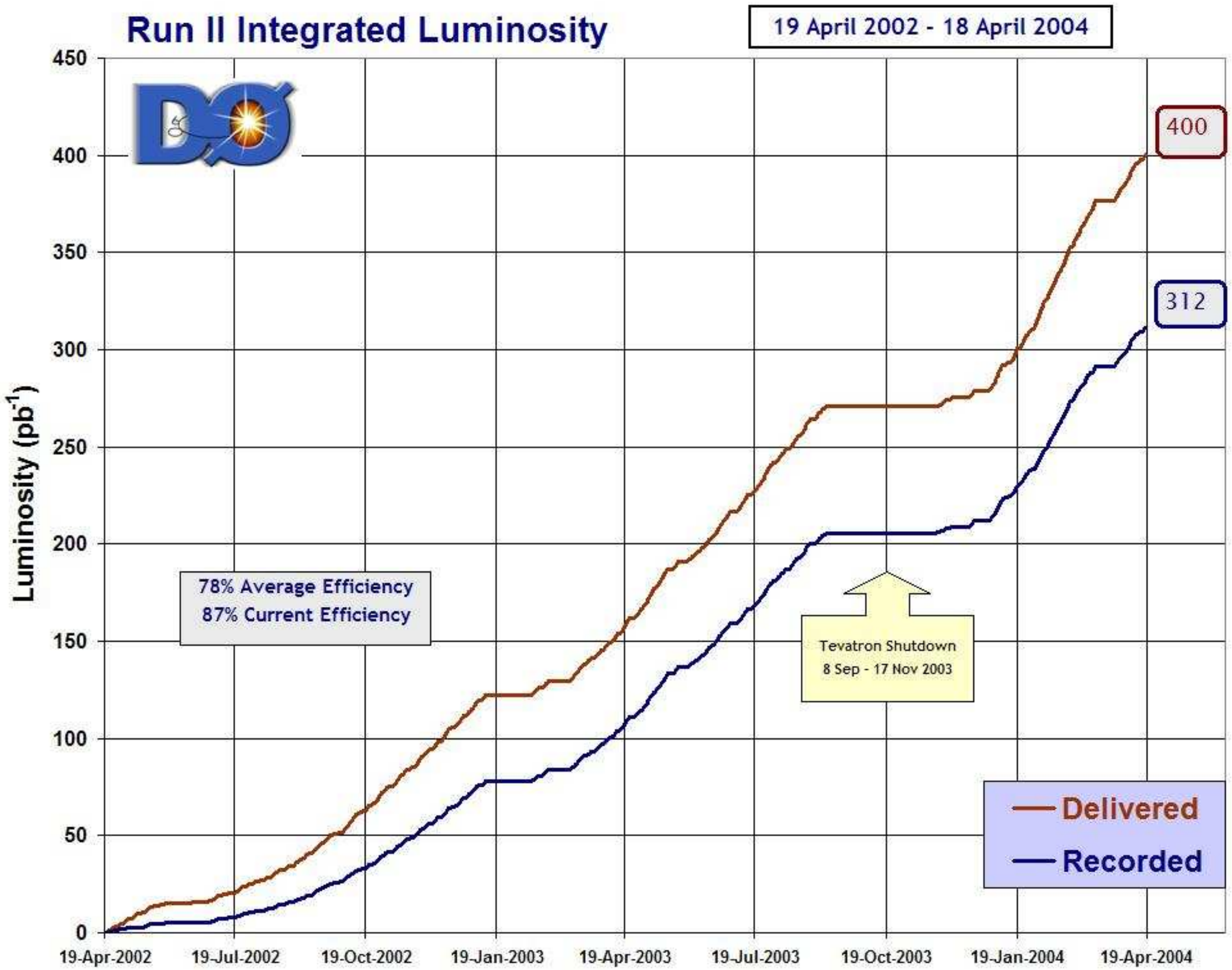
Why rare B physics at the Tevatron ?

- Producing large numbers of $b\bar{b}$ pairs
  - $\sigma(p\bar{p} \rightarrow b\bar{b}) = 150\mu$b at 2 TeV
  - $\sigma(e^+e^- \rightarrow Z^0 \rightarrow b\bar{b}) = 7$ nb
  - $\sigma(e^+e^- \rightarrow \Upsilon(4S) \rightarrow b\bar{b}) = 1$ nb
- Expect 10^{10} $b\bar{b}$ pairs pairs/year at $4 \cdot 10^{31} cm^{-2}s^{-1}$
  - fragmenting into all B-species: $B_d, B_u, B_s, \Lambda_b, \ldots$
- Exploring the B_s sector

Key points for this analysis at DØ

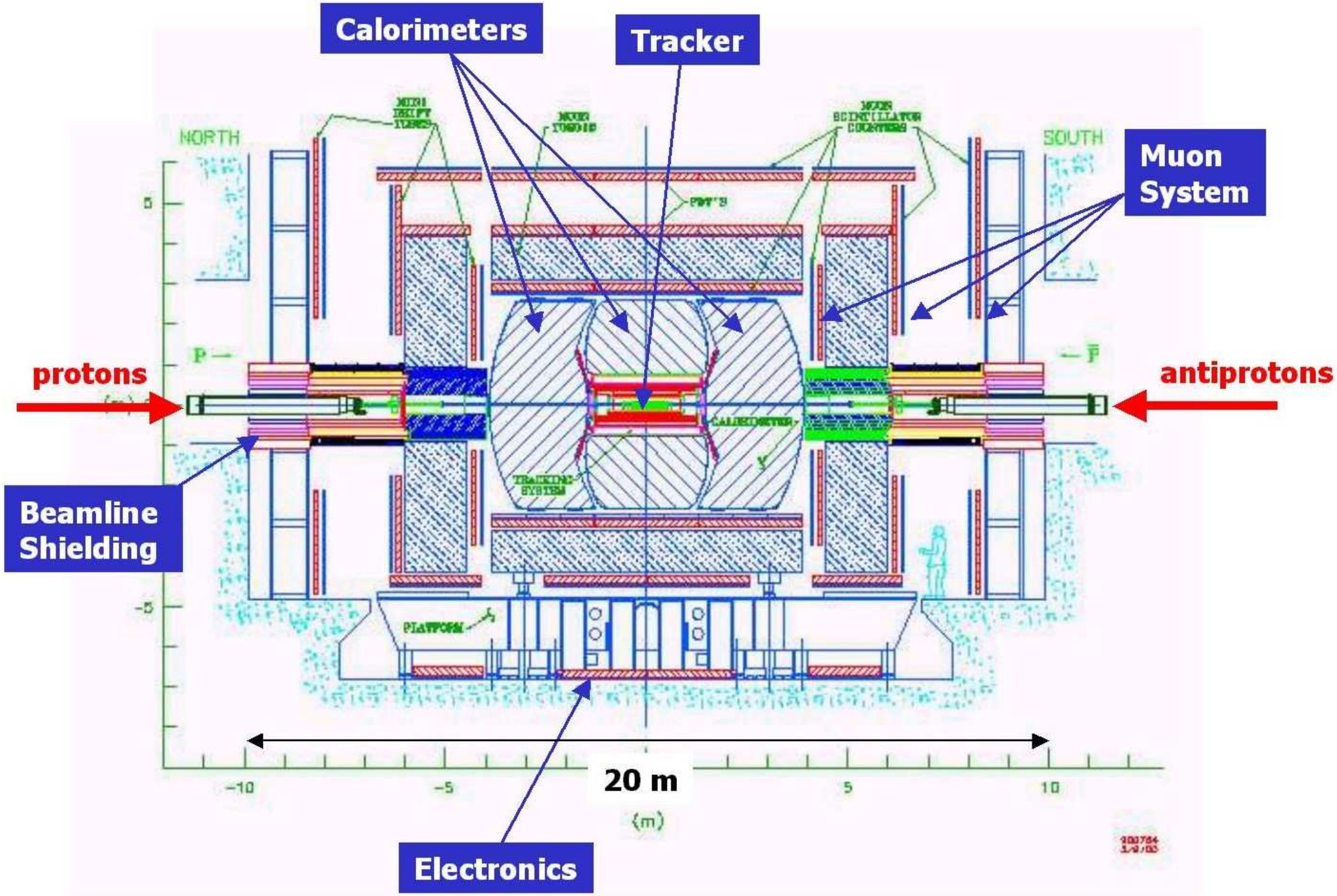
- Muon system
- Muon trigger (single and dimuon triggers)
- Silicon Vertex + Tracker

Integrated Luminosity

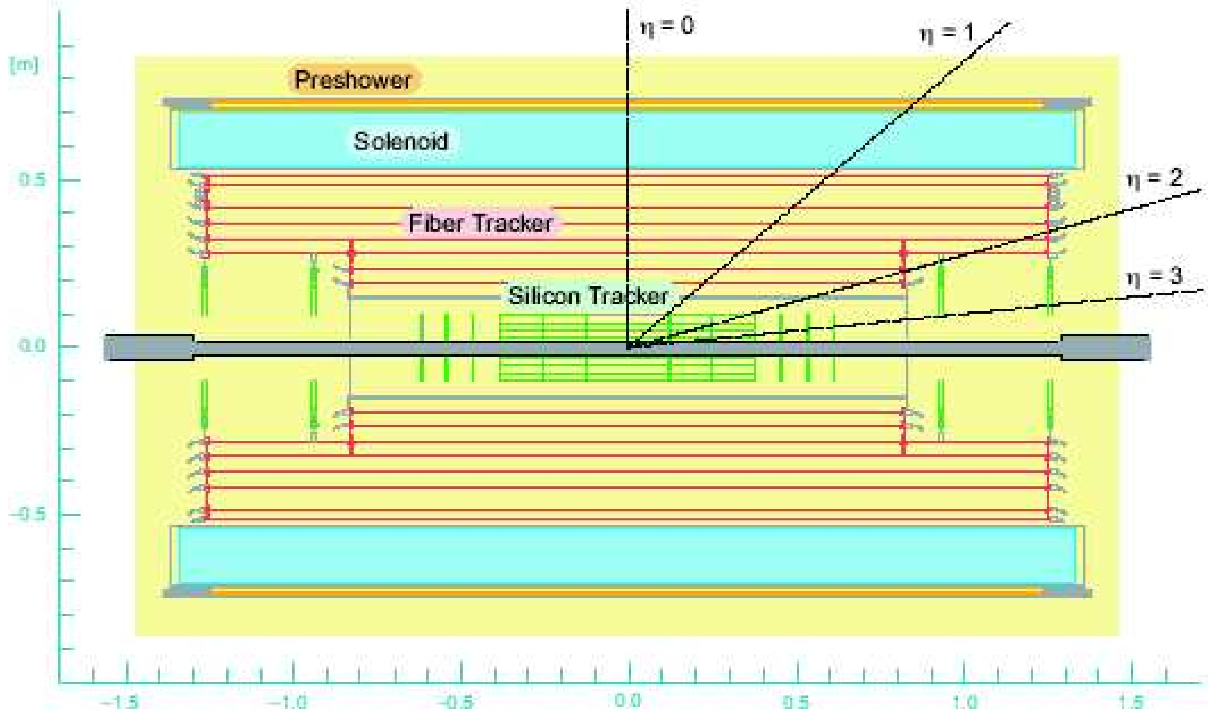


Data of Trigger used till winter shutdown gives $\approx 180\text{pb}^{-1}$

DØ Detector

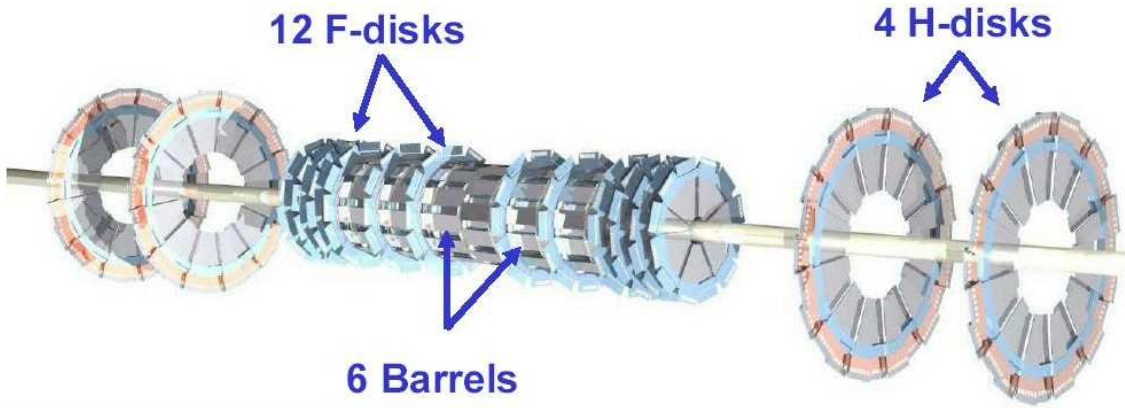

Calorimeters
Tracker
Muon System
protons
antiprotons
Beamline Shielding
Electronics
NORTH
SOUTH
20 m
(m)
-10
-5
5
10

DØ Tracking region

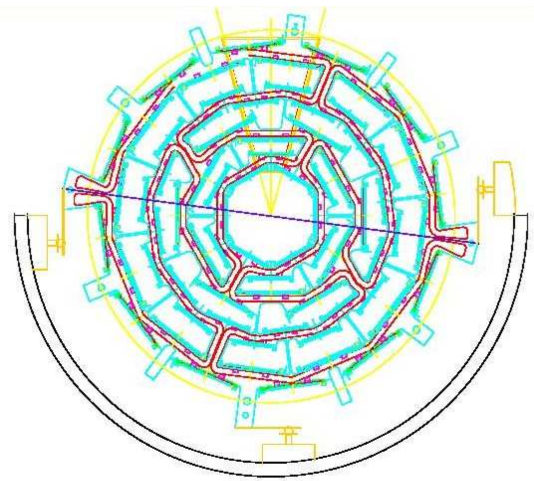


- Silicon Detector
- Fiber Tracker
  80k channels in
  8 layer axial, stereo
  VLPC readout 9K
- Superconduction
  Solenoid (2 Tesla)
- tracking/vertexing
  up to $|\eta| < 3$

DØ Silicon Microstrip Tracker (SMT)

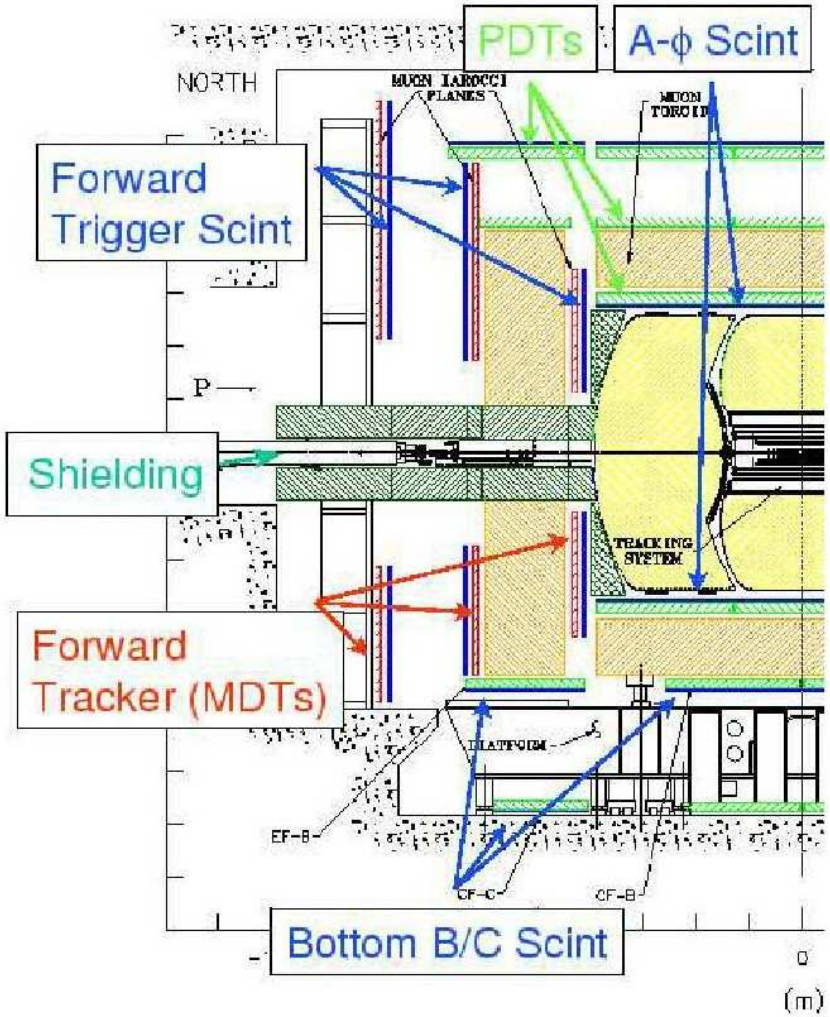


Multi-layer barrel cross-section



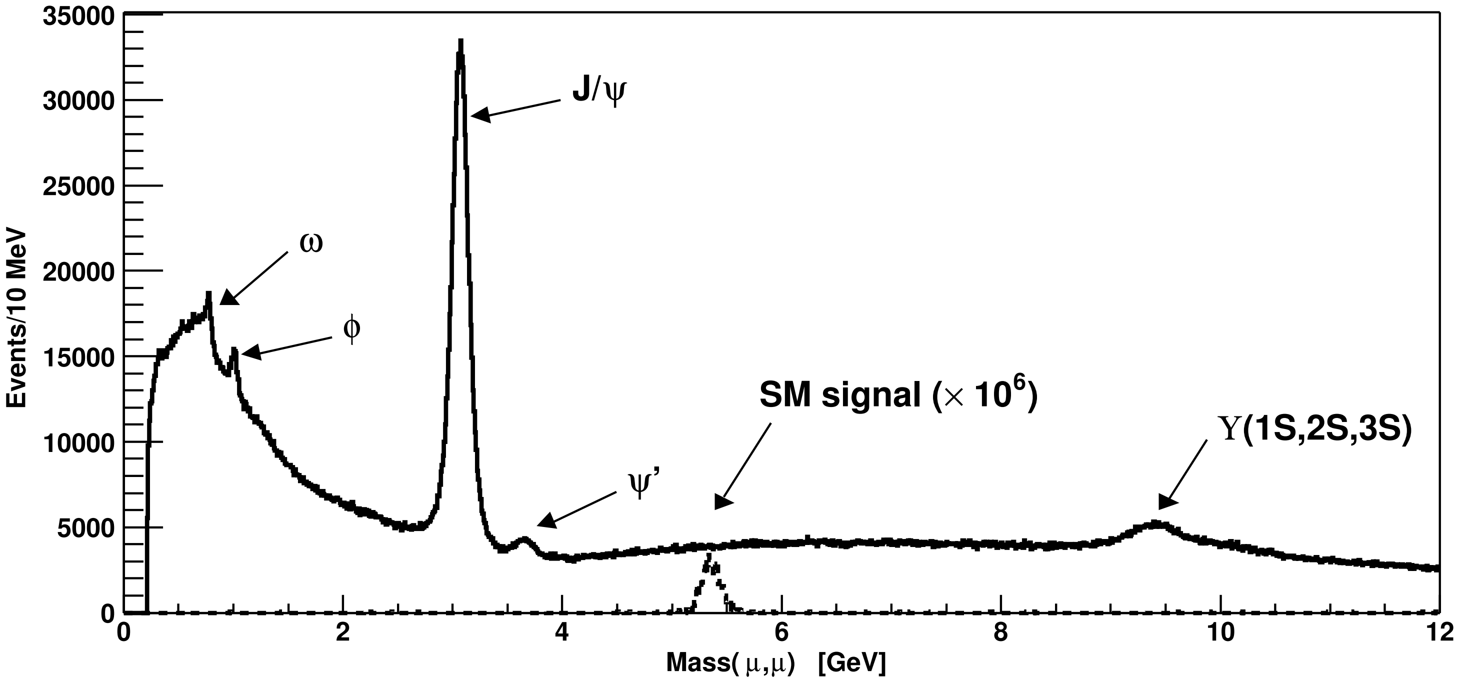
	Barrel	F-disks	H-disks
	Double+single sided	Double sided	Single sided
Stereo angle	$0°, 2°, 90°$	$\pm 15°$	$\pm 7.5°$
Channels	$\sim$ 400k	$\sim$ 250k	$\sim$ 150k
Inner radius	2.7 cm	2.6 cm	9.5 cm
Outer radius	9.4 cm	10.5 cm	26 cm

DØ Muon System



- 3 layer of drift tubes + scintillators ($\eta \leq 2$)
- Toroid magnets between 1st and 2nd layer allow stand-alone momentum measurement
- Central Proportional Drift Tubes (PDTs):
  - 6624 drift cells (10.1 cm $\times$ 5.5 cm)
  - stacked in 3- and 4- deck chambers
- Forward Mini Drift Tubes (MDTs):
  - 6080 8-cell tubes (9.4 mm $\times$ 9.4 mm)
  - provide fast L1 trigger signal
- Scintillation Counters (central + forward)
  - 4214 forward, 630 central counters
  - segmentation 0.1 mm $\times$ 4.5 mm in $\eta \times \Phi$
  - provide fast L1 trigger signal

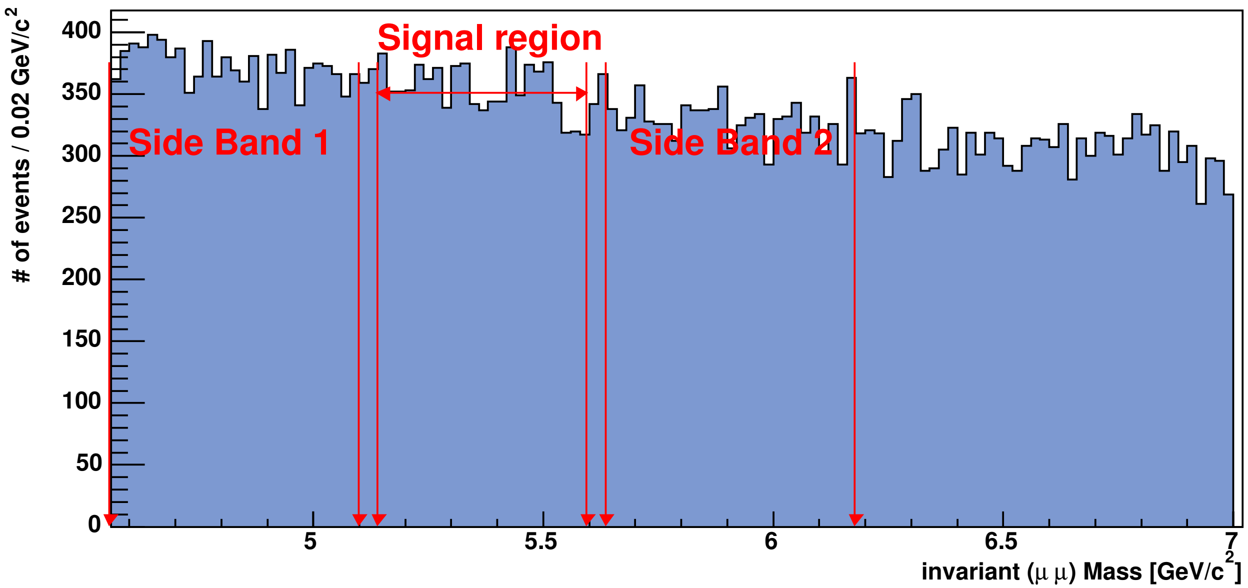
DiMuon Data sample



Selection Cuts

- Cut on Mass region of DiMuon sample $4.5 < m_{\mu\mu} < 7$ GeV
- Two muons with a net charge of zero
- The triggered muons have reconstructed tracks in the tracker
  - at least 3 hits in the Silicon Tracker
  - at least 4 hits in the Fiber Tracker
- The χ^2 of the vertex fit is smaller than 10
- The measured p_T of the muons is greater than 2 GeV
- Both muons are at least of medium quality
- A minimum p_T of the B_s candidate of 5 GeV is required
- Cut on the significance of the transverse decay length $\sigma(L_{xy}) < 150\mu m$

Selection Cuts II



45k events remain after all these cuts in mass region (4.5 - 7 GeV/c^2) → use discriminating variables

- Opening angle between the vertex direction and the muon pair "Pointing consistency"
- Isolation of the muon pair
- Decay length

Optimization procedure

- $\approx 80 pb^{-1}$ of Data have been used to optimize cuts
- Perform random grid search of the 3 discriminating variables (Use MC event properties as candidate cuts)
  - Signal region for MC is $m_{B_s} \pm 3\ \sigma$ ($1\sigma = 90$ MeV) (same applies for Data)
  - Side Band 1 from 4.560 GeV to 5.100 GeV (540 MeV)
  - Side Band 2 from 5.640 GeV to 6.180 GeV (540 MeV)
- Keep signal region as a blind box
- Maximize sensitivity of searches for new signals

$$\frac{\epsilon_{\mu^+\mu^-}}{a/2 + \sqrt{B}}$$

  following the proposal from G. Punzi (physics/0308063 test of hypothesis and limits)
  - define α as significance of the test
    a is the number of sigmas for α
    (i.e 95% $\rightarrow$ 2 σ $\rightarrow$ a=2)
  - $\epsilon_{\mu^+\mu^-}$ is the reconstruction efficiency for $B_S \rightarrow \mu^+\mu^-$
  - B is the expected number of background events in signal region

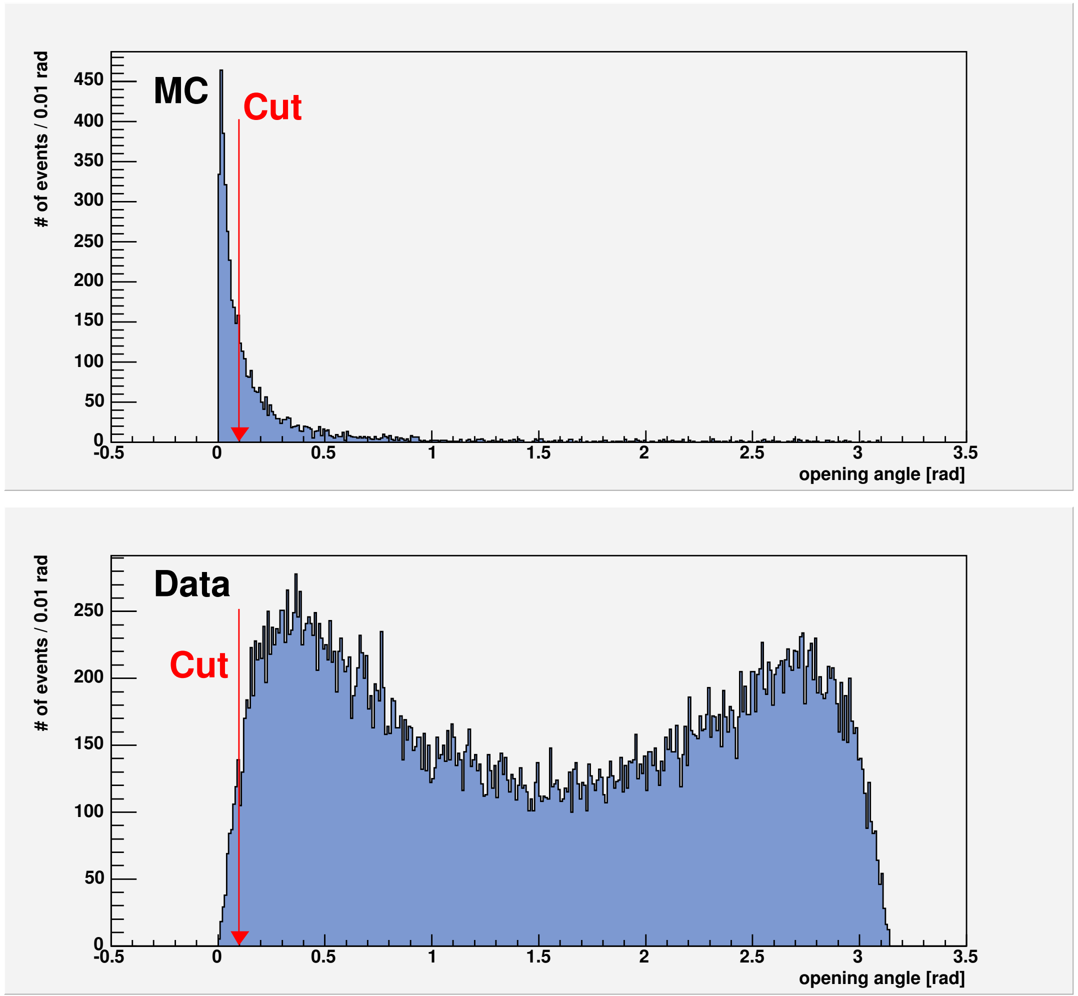
Optimization procedure II

Why use the Punzi's proposal ?

- correct statistical practice requires to decide before the experiment the values of α and CL
- $S/\sqrt{B}$ may push the experiment efficiency down to very small values
  Prefer e.g. 0.1 expected signal events with a background of 10^{-5} over 10 signal expected and 1 background event
- $S/\sqrt{S+B}$ cannot maximized without knowing the cross section for the searched signal
- independent of the expectations for a signal to be present thus allowing unbiased optimization
  - no dependence on metric or priors
  - independent of choice of a limit setting algorithm
- Punzi's proposal can be used for setting limits and discovery, by setting the constant a

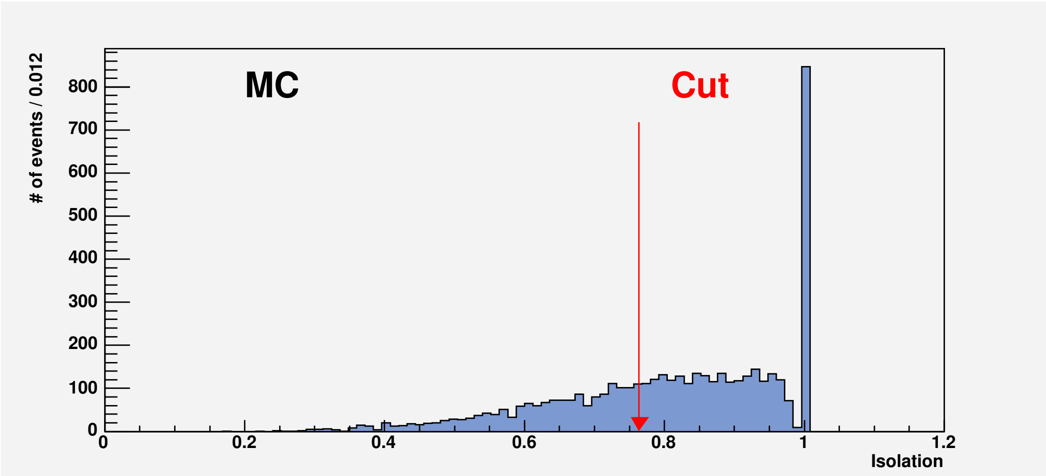
Discriminating variables I

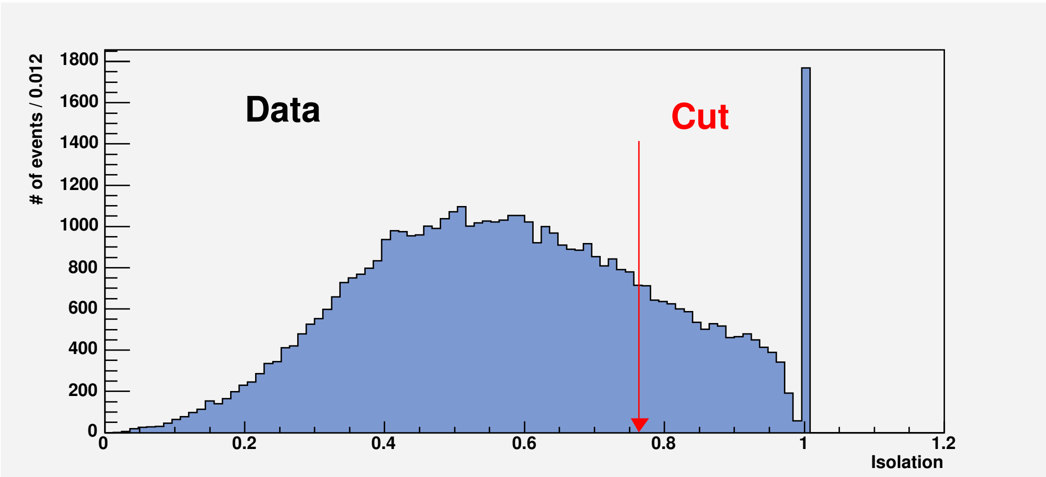
Opening angle $\alpha < 0.103$ radians



Discriminating variables II

Isolation > 0.765





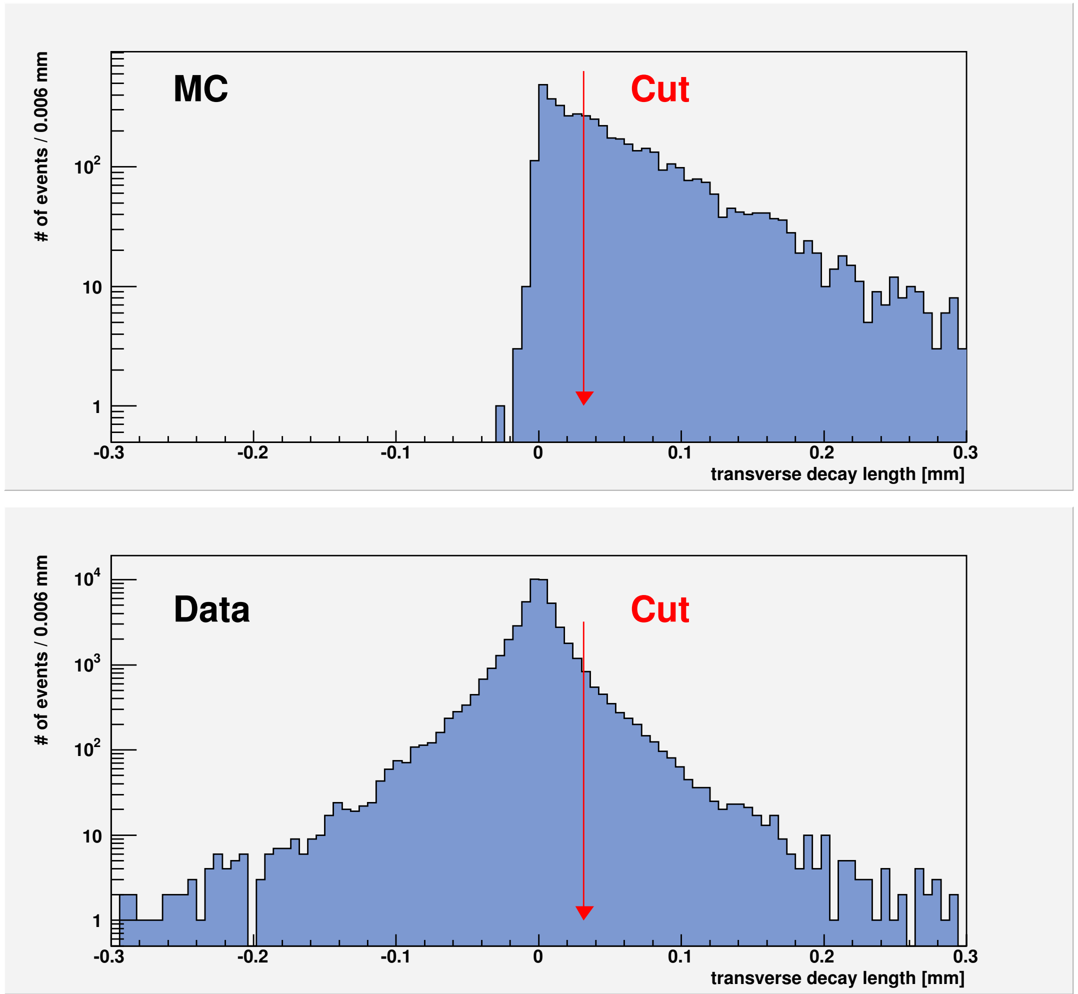
$$\mathrm{Iso} = \frac{p_{B_s}}{p_{B_s} + \sum_{\mathrm{allTracks}\,\Delta R \leq 1} p}$$

with

$$\Delta R = \sqrt{(\Delta\Phi)^2 + (\Delta\eta)^2} \leq 1$$

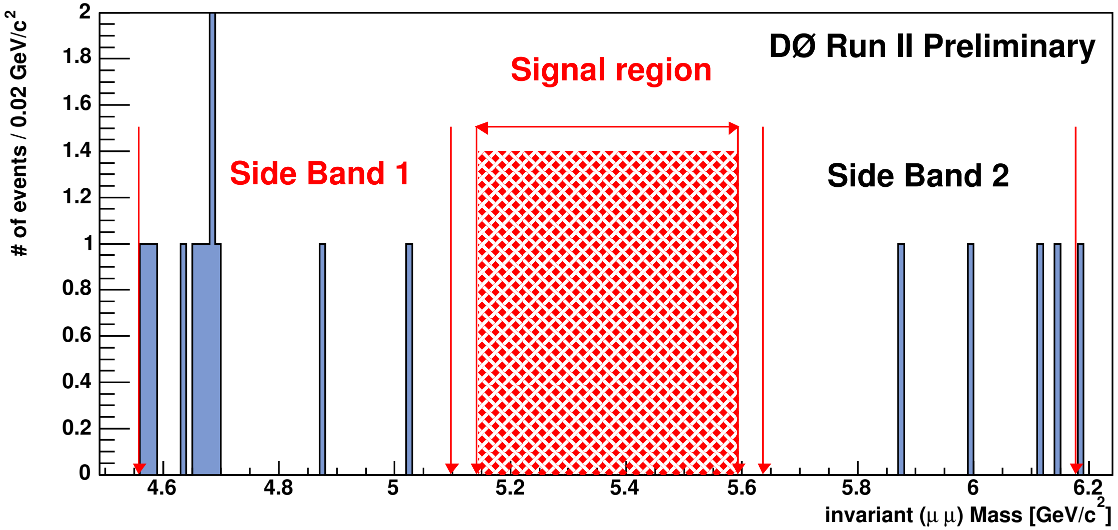
Discriminating variables III

Transverse decay length > 0.033 mm



Surviving events

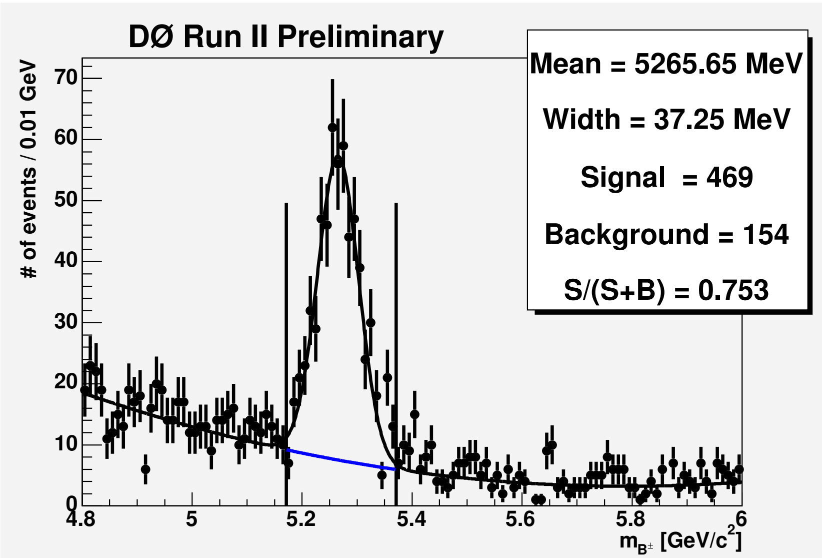
Cut	MC efficiency [%]	Signal MC	ex. Background
Pointing angle	63.4	1142	200 ± 10
Isolation	80.6	921	46 ± 4.5
Decay length	66.7	615	7.3 ± 1.8



Box not opened!

Normalizing channel $B^{\pm} \rightarrow J/\psi K^{\pm}$

- Use the decay of the $J/\psi \rightarrow \mu\mu$ to cancel $\mu\mu$ efficiencies (Apply same cuts to J/ψ like above.)
- Vertex an additional track to the J/ψ
- Additional cuts on the Kaon and $B^{\pm}$
  - Kaon pt of .9 Gev is required
  - χ^2 of the vertex fit contribution not more than 10, together not more than 20
  - Collinearity of .9 is required



Fit of a gaussian with a quadratic background

$N_{B^{\pm}} = 469 \pm 32$

Calculating the Sensitivity

without opening the box

$$BR(B_s \to \mu^+\mu^-) = \frac{N_{UL}(n_{obs}, n_B)}{N_{B^\pm}} \cdot \frac{\varepsilon_{\mu\mu K}}{\varepsilon_{\mu\mu}} \cdot \frac{b \to B^\pm}{b \to B_s} \cdot BR(B^\pm \to J/\psi K^\pm) \cdot BR(J/\psi \to \mu\mu)$$

- $N_{UL}(n_{obs}, n_B)$ is the Upper Limit calculated using the Feldman-Cousins method
- $N_{B^\pm}$ is the number of accepted $B^\pm \to J/\psi K^\pm$ events
  $N_{B^\pm} = 469 \pm 32$ events
- $\varepsilon_{\mu\mu}$ and $\varepsilon_{\mu\mu K}$ are reconstruction efficiencies
  $\varepsilon_{\mu\mu} = (5.58 \pm 0.21) \cdot 10^{-4}$ and $\varepsilon_{\mu\mu K} = (4.33 \pm 0.17) \cdot 10^{-3}$
- Correction factor for fragmentation $\frac{b \to B^\pm}{b \to B_s} = 3.91 \pm 0.72$ PDG

Expected average upper limit is calculated via

$$< BR(B_s \to \mu^+\mu^-) >= \sum_{n_{obs}=0}^{\infty} BR(n_{obs}, n_B) \cdot \frac{n_B^{n_{obs}}}{(n_{obs})!} \cdot \exp(-n_B)$$

Preliminary Results RGS

$$< BR(B_s \to \mu^+\mu^-) > \ = 9.1 \cdot 10^{-7} \text{ at } 95\% \text{ CL}$$

Folding in the uncertainty of the background and the signal efficiency (MC integration with a gaussian background and efficiency as a log-normal distribution)

$$< BR(B_s \to \mu^+\mu^-) > \ = 1.0 \cdot 10^{-6} \text{ at } 95\% \text{ CL}$$

Relative systematic uncertainties to $< BR \to \mu^+\mu^-) >$

Source	Relative Uncertainty [%]
$\mathcal{B}(B^\pm \to J/\psi K^\pm)$	4
$\mathcal{B}(J/\psi \to \mu\mu)$	2
$b \to B_s$, $b \to B^\pm$	15
MC stat for $B^\pm \to J/\psi K^\pm$	4
# of $B^\pm \to J/\psi K^\pm$	7
cut efficiency for α	5

Conclusions

- Expected average upper limit (statistical sensitivity) with in the uncertainty of the background and the signal folded in is
  $< BR(B_s \rightarrow \mu^+\mu^-) > \; = 1.0 \cdot 10^{-6}$ at 95% CL
- The box has NOT been opened yet
  - Reoptimisation still in progress (testing other dicriminating variables) - further improvements expected
- More Data will be added